Modified Magnetism at Buried Interfaces

Circularly Polarized X-Ray Standing Waves Probe Nanostructures

As we enter into the era of nanoscience where effects due to surfaces and interfaces often dominate, researchers more than ever need experimental techniques that allow them to discriminate between what goes on at the boundaries and in the interior of nanostructures. A team of two Berkeley Lab materials scientists has used x-ray standing waves generated with circularly polarized soft x rays at the Advanced Light Source to do just that for palladium/cobalt/palladium trilayers similar to those that exhibit perpendicular magnetic anisotropy (PMA). With their technique, the two researchers demonstrated quantitatively that the magnetic properties at a palladium/cobalt interface differed from those in the center of the cobalt layer. Other groups are already adopting this approach in their own studies of buried interfaces in nanolayer structures.

In a magnetic material, the magnetization usually prefers to point in certain "easy" crystallographic directions because the energy is lower. In a thin film, the easy directions typically lie in the plane of the film. PMA refers to the tendency in some ultrathin magnetic layers for the magnetization to point out of the plane, especially if the magnetic layer is also bounded by top and bottom metallic layers. PMA is one of several phenomena, such as giant magnetoresistance, exchange bias, and spin tunneling, that make devices based on nanolayer structures attractive for magnetic data storage, memory, and related applications.

To explain the basics of PMA, researchers often use a phenomenological model due to Néel in which a surface term inversely proportional to the layer thickness lowers the energy of the perpendicular relative to the in-plane orientation as the thickness decreases. However, researchers are not able to rule out other microstructural effects, such as anisotropic strain or chemical intermixing at the interface between the magnetic and metal layers, in part because experimental techniques average over depths of two to three nanometers and thus cannot resolved physical effects localized at an interface.

To address this issue, the Berkeley Lab team adapted the established technique of x-ray standing wave spectroscopy by combining it with circularly polarized synchrotron radiation. Standing waves build up within multilayer mirrors owing to the constructive and destructive interference of the waves reflected from each interface in the multilayer. Such a standing wave will extend through a PMA trilayer grown on top of the standing-wave generator. The difference in the absorption of left and right circularly polarized x rays (magnetic circular dichroism or MCD) at the cobalt L edges probes the cobalt magnetic properties. Since the depths of the periodic intensity maxima depend on the reflection (incidence) angle, it is possible to scan the standing wave vertically through the trilayer and to resolve the depth dependence of the dichroism by varying the angle.

The team chose to investigate a palladium/cobalt/palladium trilayer on a W/B_4C multilayer standing-wave generator. With the cobalt layer thickness used (2 nm), PMA does not occur but precursor interfacial effects were expected to become prominent. The experimental results showed exactly that, as the researchers obtained cobalt MCD spectra over a range of angles that probed from one palladium interface to the center of the cobalt layer. From the MCD data, they extracted values of the number of missing electrons (holes) in the magnetically active cobalt d states and of the associated spin and orbital magnetic moments. The team interpreted increases in the number of d holes and the orbital moment near the interface in terms of hybridization of cobalt with palladium states at the interface and concluded that the two-term surface magnetocrystalline anisotropy model of Néel is oversimplified. ■

Jeffrey B. Kortright (510-486-5960), Materials Sciences Division, E.O. Lawrence Berkeley National Laboratory

S.-K. Kim and J. B. Kortright, "Modified Magnetism at a Buried Co/Pd Interface Resolved with X-Ray Standing Waves," *Phys. Rev. Lett.* **86**, 1347 (2001).

RESEARCH FUNDING: U. S. Department of Energy, Office of Basic Energy Sciences (BES). Operation of the ALS is supported by BES.

MODIFIED MAGNETISM AT BURIED INTERFACES

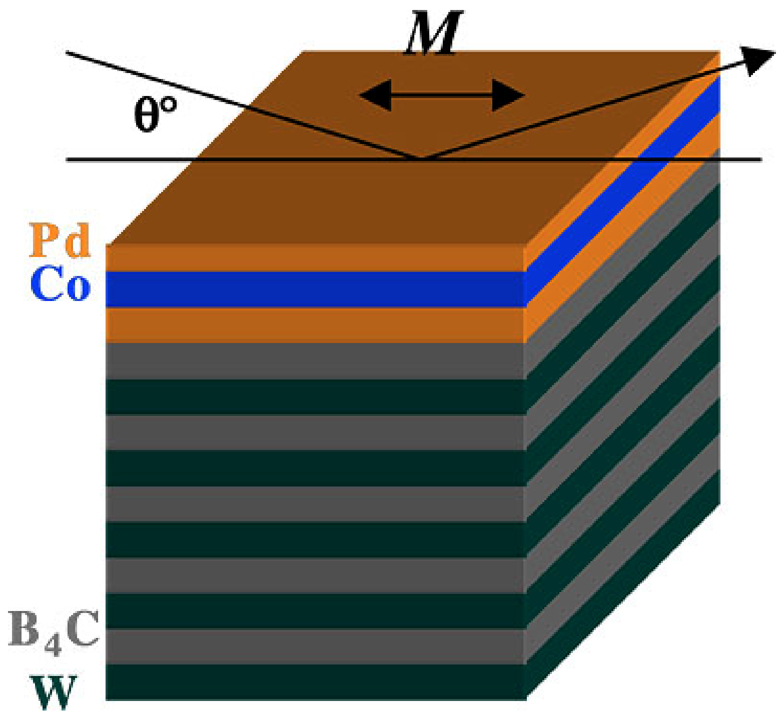
Circularly Polarized X-Ray Standing Waves Probe Nanostructures

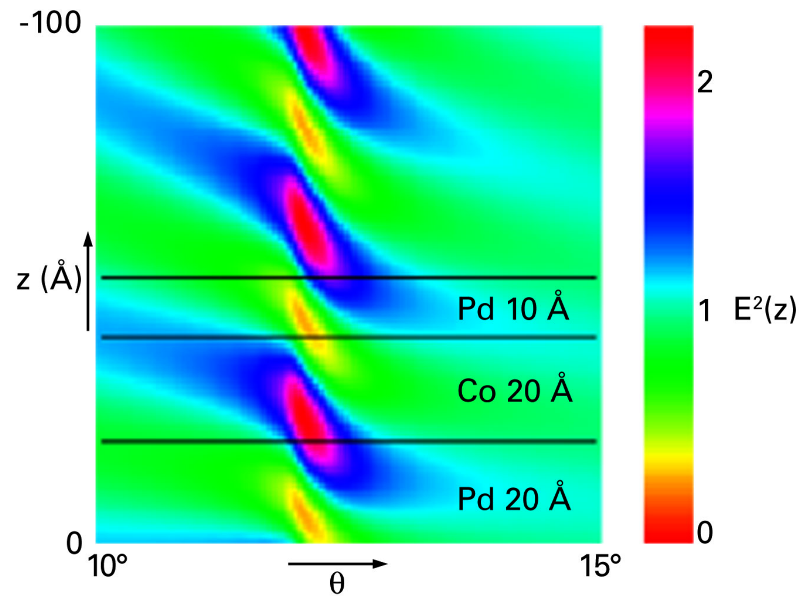
- **Interfacial effects dominate in magnetic nanostructures**
  - *Give rise to phenomena exploited in magnetic data storage, memory, and other devices*
  - *Giant magnetoresistance, exchange bias, magnetic tunneling, perpendicular magnetic anisotropy*
- **Experiments need depth resolution to unravel mechanisms**
  - *Most techniques average over a few nanometers below the surface*
  - *Separating interfacial from bulk effects with subnanometer accuracy is essential*
- **Soft x-ray standing waves serve as vertical probe**
  - *Interference generates standing waves in multilayer mirrors*
  - *Position of intensity maxima changes with angle of incidence*
- **Circularly polarized standing waves reveal interface magnetism**
  - *Applied to Pd/Co/Pd trilayer on a B_4C/W multilayer at the Advanced Light Source*
  - *Magnetic circular dichroism yields number of d-state holes and oribital and spin moments*
  - *Depth dependence interpreted in terms of chemical intermixing across the interface*
  - *Technique generally applicable to other magnetic nanostructures*

S.-K. Kim (Berkeley Lab and Korea Advanced Institute of Science and Technology) and J.B. Kortright (Berkeley Lab).
[*Phys. Rev. Lett.* 86, 1347 (2001)]

MODIFIED MAGNETISM AT BURIED INTERFACES

Circularly Polarized X-Ray Standing Waves Probe Nanostructures



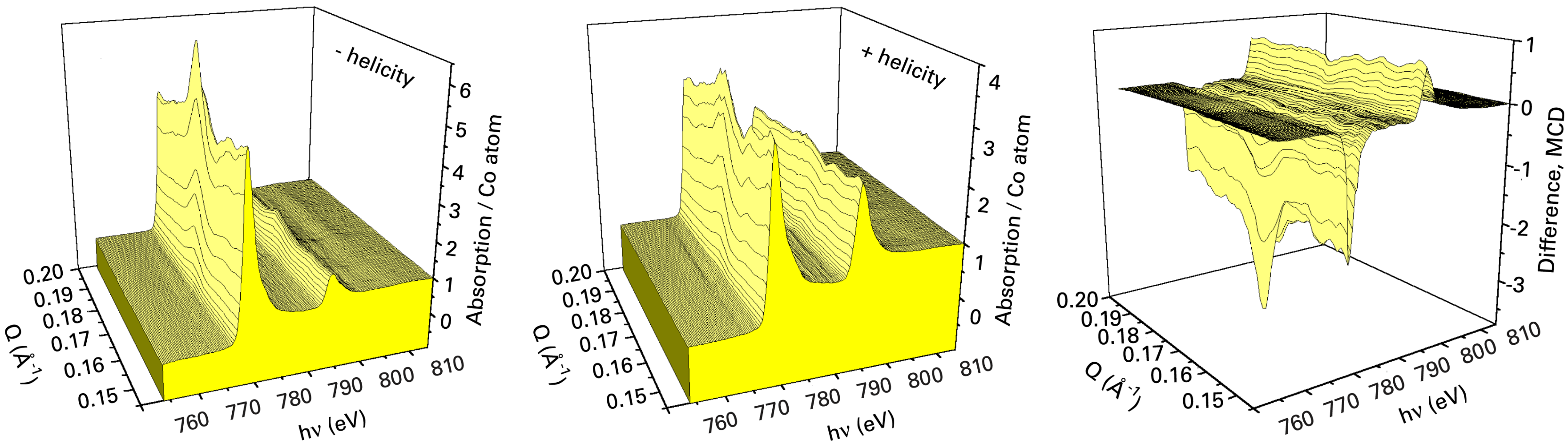


X rays reflecting from the B_4C/W multilayer generate a standing wave pattern that extends into the overlying Pd/Co/Pd trilayer. The intensity distribution of the standing wave varies with angle of incidence θ, thereby providing a way to examine how magnetic behavior varies with depth z in the Co.

S.-K. Kim (Berkeley Lab and Korea Advanced Institute of Science and Technology) and J.B. Kortright (Berkeley Lab).
[*Phys. Rev. Lett.* 86, 1347 (2001)]

MODIFIED MAGNETISM AT BURIED INTERFACES

Circularly Polarized X-Ray Standing Waves Probe Nanostructures

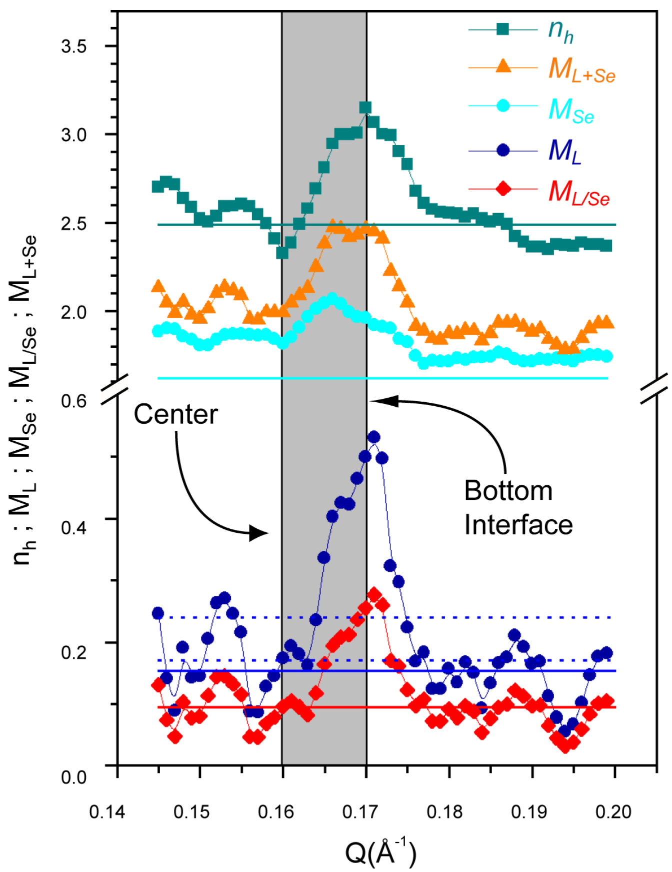


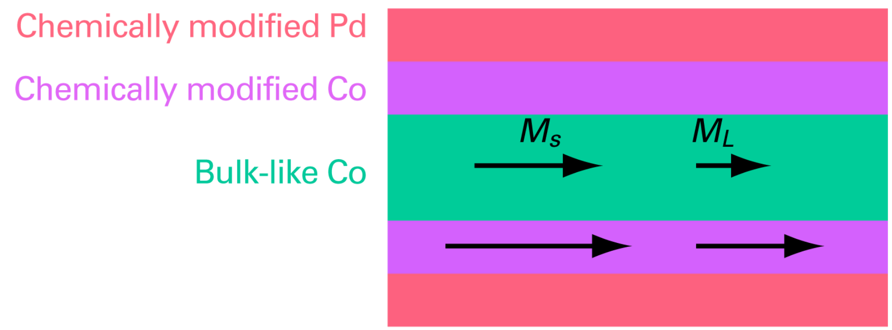
Absorption by Co of a standing wave consisting of circularly polarized x rays varies not only with photon energy and the helicity of the polarization but with the scattering vector Q (related to the reflection angle θ). Q scans show that the absorption and, hence, the magnetic properties, are different in the middle of the Co layer (Q = 0.16) and at the interface with Pd (Q = 0.17).

S.-K. Kim (Berkeley Lab and Korea Advanced Institute of Science and Technology) and J.B. Kortright (Berkeley Lab).
[*Phys. Rev. Lett.* 86, 1347 (2001)]

MODIFIED MAGNETISM AT BURIED INTERFACES

Circularly Polarized X-Ray Standing Waves Probe Nanostructures





Analysis of the depth-dependent magnetic circular dichroism spectra yield the number of holes n_h in d states and their orbital and spin magnetic moments in the Co layer. The changing values with depth suggest a model attributing the behavior to chemical modifications near the Co/Pd interface.

S.-K. Kim (Berkeley Lab and Korea Advanced Institute of Science and Technology) and J.B. Kortright (Berkeley Lab).
[*Phys. Rev. Lett.* 86, 1347 (2001)]